

KGKU-99-01 / MIE-99-01

hep-ph/9902472

Revised Version

Self-Dual Point and Unification

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Abstract

We hypothesize that the vacuum is spontaneously shifted from the self-dual point in the moduli space, at which all dimensions are compact, and that the true vacuum results from the decompactification of the four space-time dimensions and remains in the vicinity of the self-dual point for extra dimensions. On the basis of our hypotheses we explore new types of the coupling unification which are not realized in the four-dimensional effective theory but in the framework of the higher dimensional theory. In the $SU(6) \times SU(2)_R$ string model, if the $SU(6)$ gauge group lives in the world-volume of 9-branes and the $SU(2)_R$ in the world-volume of 5-branes, or *vice versa*, unification solutions can be found in the vicinity of the self-dual point.

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1 Introduction

The recent advances in string theory have been stimulated by new concepts of non-perturbative string dualities and D-branes.[1]-[5] Using the string dualities it has been suggested that all five known perturbative superstring theories correspond to different particular limits of the underlying eleven-dimensional theory (M-theory), or twelve-dimensional theory (F-theory). In addition, in string theory there exist higher dimensional extended solitonic objects (D-branes). In the light of the dualities it is known that there is no absolute distinction between strings and solitonic objects. Therefore, the underlying theory is not simply a theory of string but a theory of extended objects including both strings and branes.

New aspects of string phenomenology have opened up due to recent developments in string theory. In fact, it has been found that there are new regions of the moduli space which are not contained in perturbative string theories. For instance, it is possible that some part of the gauge group and the matter content in the low-energy effective theory has a non-perturbative origin and that the other part of them has a perturbative origin. In addition, the string scale could lie somewhere between $\sim 1\text{TeV}$ and the Planck scale M_{Pl} . It should be emphasized that the coupling unification is properly realized in the framework of the higher-dimensional underlying theory. This does not necessarily mean that gauge couplings in the four-dimensional effective theory join at a certain energy scale. As a consequence, various paths seem to be possible for connecting the higher-dimensional underlying theory with low energy physics. Among them, the scenario of large extra dimensions has been extensively studied.[6]-[13] However, since proton stability suggests the existence of a large energy scale, it is unlikely that all extra dimensions are large in radius. The coexistence of large and small extra dimensions results in the fine-tuning problem.

The purpose of this paper is to explore new types of unification solutions without the fine-tuning that provide an alternative to the scenario of large extra dimensions. From the viewpoint of the unified theory, it is likely that the universe starts from a special point in the moduli space at which the symmetry of the underlying theory is maximally enhanced. This point should be a self-dual point in the moduli space for all dimensions, including the four space-time dimensions. It is hypothesized that the maximal symmetry is spontaneously broken due to some non-perturbative dynamics and that the decompactification occurs only for the four space-time dimensions. The beginning of the decompactification corresponds to the Big Bang. On the other hand, it is presumed that the non-perturbative dynamics also affects the sizes of the other dimensions, but the rate of their change is of order unity. Namely, as for extra dimensions other than the four space-time dimensions, the true vacuum remains in the vicinity of the self-dual point. Therefore, as far as extra dimensions are concerned, we are free from the fine-tuning problem. In this paper, based on our hypotheses we explore new types of the coupling unification that are not realized in the four-

dimensional effective theory but only in the framework of the higher-dimensional theory.

This paper is organized as follows. In section 2 we give some hypotheses concerning the symmetry of the underlying theory. As mentioned above, we expect that starting from the self-dual point in the moduli space for all dimensions, the vacuum is shifted from that point. However, the true vacuum resides in the vicinity of the self-dual point for extra dimensions. In section 3 the unification problem is discussed in the framework of the Type IIB orientifold. On the basis of the brane picture, we explore new types of the coupling unification that are not contained in perturbative string theories. In the $SU(6) \times SU(2)_R$ string model, if the $SU(6)$ gauge group lives in the world-volume of 9-branes and the $SU(2)_R$ in the world-volume of 5-branes, or *vice versa*, we find unification solutions in the vicinity of the self-dual point in the moduli space. The final section is devoted to summary and discussion.

2 Self-dual point and decompactification

In this section we give hypotheses with regard to the underlying theory. If we follow the viewpoint of the unified theory thoroughly, it is natural that the underlying theory has the maximal symmetry allowed in its own theoretical framework. This implies that the vacuum of the underlying theory resides at the self-dual point in the moduli space for all dimensions, including the four space-time dimensions. This hypothesis is reasonable in view of the fact that in the heterotic superstring theory the maximal enhancement of the gauge symmetry occurs when the 16-dimensional compact space is an even self-dual lattice, which is required by the modular invariance. The hypothesis that the ground state of string theory lies at a point of maximally enhanced symmetry has been discussed by Dine et al. [14] They have assumed that this point corresponds to the self-dual point with respect to the modular transformation of moduli fields in the framework of the four-dimensional effective theory. On the other hand, according to our hypothesis the self-dual point is concerned with the S - and T -duality transformations defined in the framework of the higher-dimensional underlying theory. Furthermore, as is discussed below, the emphasis is placed on the D-brane configurations in the vacuum.

In the S -duality, the string coupling constant g_{st} is transformed as

$$g_{\text{st}} \longrightarrow g'_{\text{st}} = \frac{1}{g_{\text{st}}}, \quad (1)$$

where $g_{\text{st}} = \exp(\langle\phi\rangle)$ and ϕ is the dilaton field. Thus the self-dual point with respect to the S -duality is

$$g_{\text{st}} = 1, \quad (2)$$

which implies $\langle\phi\rangle = 0$. In the framework of F-theory, the S -duality transformation is contained in the modular transformation for the eleventh and the twelfth

coordinates.[5] On the other hand, under the T -duality transformation, the size R of the compact space and the string coupling constant are transformed as

$$R \longrightarrow \tilde{R} = \frac{\alpha'}{R}, \quad (3)$$

$$g_{\text{st}} \longrightarrow \tilde{g}_{\text{st}} = g_{\text{st}} \frac{\sqrt{\alpha'}}{R}. \quad (4)$$

In what follows we use the notation M_*^{-2} for α' . The mass scale M_* represents the fundamental scale of the theory. With this notation the self-dual point with respect to the T -duality is given by

$$R = M_*^{-1}. \quad (5)$$

At this point we have $\tilde{g}_{\text{st}} = g_{\text{st}}$.

The first ansatz is that the universe started from the above self-dual point with respect to both the S -duality and the T -duality, at which all dimensions are compact and their size and shape are appropriately quantized. The second ansatz is that some portion of the maximal symmetry was spontaneously broken due to some unknown dynamics and that the universe was shifted from the self-dual point. Depending upon the shifted location of the vacuum in the moduli space, we have various types of the higher-dimensional theory. The five known ten-dimensional superstring theories correspond to different types of the decompactification of ten dimensions. The true vacuum results from the decompactification of only the four space-time dimensions; that is, in the true vacuum, only four dimensions began expanding, and their sizes are approximately 1.2×10^{10} light-yr. As for the other dimensions it is assumed that the universe remains in the vicinity of the self-dual point. In the context of the non-perturbative dynamics one should not ask why extra dimensions are compactified, but instead why the four space-time dimensions are decompactified.

The situation after the Big Bang is described by the four-dimensional effective theory. The size and shape of the compact space can be expressed in terms of the moduli fields T_i in the effective theory. In fact, the vacuum expectation values (VEVs) of these fields are related to the sizes of the compact space along different directions. The moduli fields T_i carry the charges of the family symmetry. As is well known, in nature the family symmetry is broken. For instance, since Yukawa couplings have hierarchical family structure, it is obvious that the family symmetry is broken in Yukawa couplings. Therefore, the moduli fields T_i , which have different quantum numbers of the family symmetry, do not necessarily have the same VEV. This means that the universe now be shifted from the self-dual point with respect to the T -duality for extra dimensions and that the sizes of the compact space may differ, depending on the directions. The second ansatz mentioned above is that the universe resides in the region of the moduli space as

$$g_{\text{st}} = O(1) \quad \text{and} \quad RM_* = O(1). \quad (6)$$

In the next section, by assuming $g_{\text{st}} \sim 1$, we explore unification solutions consistent with Eq. (6).

Based on the above ansatze we explore new types of unification in which different types of D-branes possibly coexist. On the other hand, in Ref.[14] the coexistence of different types of D-branes has not been taken into account. Hence the discussion in Ref.[14] does not mention the possibility that the standard model is embedded separately into different types of D-branes.

3 New types of the coupling unification

The unification of gauge couplings and the gravitational coupling is properly realized in the framework of the higher-dimensional theory. The scales which appear in the four-dimensional effective theory do not necessarily represent the fundamental scale by itself. This implies that there possibly exist new types of the coupling unification that are realized in the framework of the higher-dimensional theory but not in the four-dimensional effective theory. To be specific, we take the Type IIB orientifold formulation, which corresponds to the Type I string theory. The bosonic part of the ten-dimensional action for the Type IIB orientifold[15] [16] [17] is

$$S_{10} = - \int \frac{d^{10}x}{(2\pi)^7} \sqrt{-g} \left(\frac{M_*^8}{g_{\text{st}}^2} R + \frac{M_*^6}{g_{\text{st}}} \frac{1}{4} F_{(9)}^2 + \cdots \right), \quad (7)$$

where $F_{(9)}$ refers to the gauge field coming from the 32 9-branes. Generally, when the six-dimensional compact space is moded out by the discrete subgroup of $SO(6)$, the anomaly of R-R charges emerges. The consistency of the theory requires the cancellation of the anomaly, and then D-branes with various configurations should be added. This type of string vacuum is expected to be dual to a non-perturbative heterotic vacuum. In this case the gravity lives in the ten-dimensional bulk. On the other hand, the gauge groups live in the world volume of Dp -branes with $p = 3, 5, 7$ and 9. Several authors[16][18] have constructed four-dimensional Z_N and $Z_N \times Z_M$ orientifolds with different configurations of 5-branes, 7-branes and 9-branes. D-brane configurations are constrained strongly, depending on the orientifold group. If both Dp -branes and Dq -branes appear in the theory, the condition

$$p - q \equiv 0, \quad \text{mod } 4 \quad (8)$$

should be satisfied in order to preserve $N = 1$ SUSY in the four-dimensional effective theory.[1] In this paper we do not discuss the dependence of the D-brane configuration on the orientifold group. Instead, we study unification solutions from the phenomenological point of view on the supposition of some appropriate D-brane configurations. After dimensional reduction down to four dimensions, we obtain the bosonic part of

the action,

$$S_4 = - \int \frac{d^4x}{2\pi} \sqrt{-g} \left(\frac{M_*^8 V_6}{g_{\text{st}}^2 (2\pi)^6} R + \sum_{p=3}^9 \frac{M_*^{p-3} V_{p-3}}{g_{\text{st}} (2\pi)^{p-3}} \frac{1}{4} F_{(p)}^2 + \dots \right), \quad (9)$$

where the second terms represent the contribution of different Dp -branes with $p = 3, 5, 7$ and 9 and V_{p-3} is the $(p-3)$ -dimensional volume occupied by the Dp -brane in the compact space.

The new concept of D-branes opened up diverse paths of connecting the higher-dimensional underlying theory with low energy physics. Let us explore new types of the unification which are not contained in perturbative string theories. It is desirable for us to obtain unification solutions without fine-tuning. We consider two cases, one in which the standard model is embedded into a single type of branes and one in which it is not.

Case 1

In this case the standard model is embedded into a single type of branes and then four-dimensional gauge couplings meet at a certain scale (M_{GUT}). Therefore, this type of gauge unification is similar to conventional unification. From Eq. (9) we have the relations

$$M_{\text{Pl}}^2 = 8g_{\text{st}}^{-2} \frac{V_6}{(2\pi)^6} M_*^8, \quad (10)$$

$$\alpha_G^{-1} = 2g_{\text{st}}^{-1} \frac{V_{p-3}}{(2\pi)^{p-3}} M_*^{p-3}. \quad (11)$$

Since the vacuum considered here is on the border of the perturbative region of the moduli space, these relations may be subject to radiative corrections. However, since the assumed maximal symmetry of the underlying theory implies that massive spectra have $N = 4$ SUSY structure, it is expected that the tree-level relations are applicable even in the non-perturbative region of the moduli space.[6]

For simplicity, for the moment we neglect the difference of the sizes along various directions in the compact space. In such a case, the $(p-3)$ -dimensional volume can be simply expressed as

$$V_{p-3} = (2\pi R)^{p-3}. \quad (12)$$

By taking $g_{\text{st}} \sim 1$ and $\alpha_G^{-1} \sim 24$ as inputs, we obtain

$$(RM_*)^{p-3} \sim 12, \quad (13)$$

$$R^{-1} \sim \frac{1}{2\sqrt{2}} (12)^{-4/(p-3)} M_{\text{Pl}}. \quad (14)$$

Furthermore, when the perturbative unification of the gauge couplings is realized at the scale $M_{\text{GUT}} \sim 2 \times 10^{16}$ GeV as in the MSSM, it is natural for R^{-1} to be identified as M_{GUT} . If this is the case, Eq. (14) holds only for

$$p = 5, \quad (15)$$

and we have

$$RM_* \sim 3.5, \quad M_* \sim 7 \times 10^{16} \text{GeV}. \quad (16)$$

This solution implies that the standard model gauge group lives in the world-volume of 5-branes and that the size of the compact space is $O(1)$ in M_*^{-1} units. The Planck scale M_{Pl} is larger than M_* by about two orders of magnitude. This is attributable to the difference between the dimensions of the branes. Recently, proton stability has been restudied in SUSY-GUT models. [19] In these studies it was found that colored Higgs masses should be larger than $M_{\text{GUT}} \sim 2 \times 10^{16}$ GeV. This suggests that the perturbative unification of gauge couplings at $M_{\text{GUT}} \sim 2 \times 10^{16}$ GeV, such as in the MSSM, may be accidental. On the supposition that the unification bears no resemblance to the conventional one, we proceed to study the second case.

Case 2

In this case the standard model is not embedded into a single type of brane. More concretely, we consider the case in which two gauge groups are not unified in the four-dimensional effective theory. The gauge group G at the unification scale is written as

$$G = G_p \times G_q. \quad (17)$$

The gauge group G_p (G_q) lives in the world-volume of the p (q)-brane. Similarly to the previous case, we have the relations

$$M_{\text{Pl}}^2 = 8g_{\text{st}}^{-2} \frac{V_6}{(2\pi)^6} M_*^8, \quad (18)$$

$$\alpha_p^{-1} = 2g_{\text{st}}^{-1} \frac{V_{p-3}}{(2\pi)^{p-3}} M_*^{p-3}, \quad (19)$$

$$\alpha_q^{-1} = 2g_{\text{st}}^{-1} \frac{V_{q-3}}{(2\pi)^{q-3}} M_*^{q-3}. \quad (20)$$

As mentioned above, we require the condition

$$p - q \equiv 0, \quad \text{mod } 4. \quad (21)$$

If both α_p^{-1} and α_q^{-1} are larger than $2g_{\text{st}}^{-1}$, then $p, q \neq 3$. Therefore, if we assume $p \neq q$, the solutions become

$$(p, q) = (9, 5), \quad (5, 9). \quad (22)$$

Note that the 9-brane and 5-brane can be interchanged by a T -duality transformation with respect to four dimensions in the six-dimensional compact space. Thus, if the vacuum is self-dual with respect to this T -duality, then $G_p = G_q$ should be satisfied. Conversely, if $G_p \neq G_q$, the vacuum is not self-dual with respect to the T -duality. If $p = q$, we have $p = q = 5, 7$. Although the dimensions of the two branes are the same in these cases, the brane configurations should be different. In this paper we do not discuss these cases.

Here we take up a phenomenologically viable string model with the gauge group $SU(6) \times SU(2)_R$, which can explain the hierarchical pattern of quark-lepton masses and mixings systematically.[20] The gauge groups $SU(3)_c$ and $SU(2)_L$ in the standard model are included in this $SU(6)$, but $U(1)_Y$ is not. In spite of such attractive results of this model, we had not been successful in obtaining the perturbative unification of gauge couplings. As a matter of fact, the analysis in Ref.[20] shows that the numerical values of the gauge couplings are

$$\alpha(SU(6))^{-1} \sim 16, \quad \alpha(SU(2)_R)^{-1} \sim 10 \quad (23)$$

at the scale $(0.5 \sim 1) \times 10^{18}$ GeV. Let us apply these results to the present framework with $g_{st} \sim 1$. By taking $G_p = SU(6)$, $G_q = SU(2)_R$ and $(p, q) = (9, 5)$, we obtain

$$M_{Pl}^2 \sim 8 \frac{V_6}{(2\pi)^6} M_*^8, \quad (24)$$

$$16 \sim 2 \frac{V_6}{(2\pi)^6} M_*^6, \quad (25)$$

$$10 \sim 2 \frac{V_2}{(2\pi)^2} M_*^2. \quad (26)$$

The geometrical average of the size of the two extra dimensions on which the 5-brane lives is given by

$$R_2 = \frac{1}{2\pi} \sqrt{V_2} \sim 2.2 \times M_*^{-1}. \quad (27)$$

The geometrically averaged size of the four extra dimensions perpendicular to the 5-brane becomes

$$R_4 = \frac{1}{2\pi} \left(\frac{V_6}{V_2} \right)^{1/4} \sim 1.1 \times M_*^{-1}. \quad (28)$$

In this case the fundamental scale is

$$M_* \sim 1.5 \times 10^{18} \text{ GeV}. \quad (29)$$

The value $R_2^{-1} \sim 0.7 \times 10^{18}$ GeV is consistent with the result in Ref.[20]. It should be noted that in the present solution the sizes of the six-dimensional compact space (R_2 and R_4) is $O(1)$ in M_*^{-1} units. In the narrow energy region ranging from $R_2^{-1}(R_4^{-1})$

to M_* we have the contributions of KK-modes in the $R_2(R_4)$ -direction. In the energy region below R_2^{-1} , we can neglect the contributions of the KK-modes and the winding modes and obtain a four-dimensional effective theory. Furthermore, when $(p, q) = (5, 9)$, we obtain

$$R_2 \sim 2.8 \times M_*^{-1}, \quad (30)$$

$$R_4 \sim 0.9 \times M_*^{-1}, \quad (31)$$

$$M_* \sim 1.9 \times 10^{18} \text{ GeV}. \quad (32)$$

4 Summary and discussion

In this paper we have made some hypotheses regarding the higher-dimensional underlying theory. The first is that the underlying theory has the maximal symmetry allowed in its own theoretical framework. This implies that the universe starts from the self-dual point with respect to both the S -duality and the T -duality, at which all dimensions are compact. The second is that, due to some dynamics, the decompactification occurs for the four space-time dimensions and that the true vacuum remains in the vicinity of the self-dual point for extra dimensions. The unification of gauge couplings and the gravitational coupling is realized properly in the framework of the higher-dimensional theory with strings and D-branes. We explored new types of unification solutions which are not contained in perturbative string theories. If the standard model is embedded in a single type of D-brane, four-dimensional gauge couplings meet at a certain scale. On the other hand, if the standard model is not embedded in a single type of brane, we have new solutions of the coupling unification in which the four-dimensional gauge couplings do not join at a certain scale. Based on our hypotheses we studied phenomenologically viable solutions of the unification with

$$g_{\text{st}} \sim 1 \quad \text{and} \quad RM_* = O(1). \quad (33)$$

It should be emphasized that in solutions of this type, as far as extra dimensions are concerned, we are free from the fine-tuning problem. In the $SU(6) \times SU(2)_R$ string model, if the $SU(6)$ gauge group lives in the world-volume of 9-branes and the $SU(2)_R$ in the world-volume of 5-branes, or *vice versa*, we find such unification solutions in the vicinity of the self-dual point in the moduli space. In this paper we did not discuss the dependence of the D-brane configuration on the orientifold group. A study of this subject will be made elsewhere.

In this study we concentrated on the gauge group and gauge couplings. It is also important to determine what types of charged matter chiral superfields appear in the four-dimensional effective theory, depending on the brane configuration in the vacuum. In the $SU(6) \times SU(2)_R$ string model, in which 9-branes coexist with 5-branes, we have three types of charged matter superfields. In the Type I formulation, they

are (i) open strings starting and ending on 9-branes, (ii) open strings starting on 9-branes and ending on 5-branes, and (iii) open strings starting and ending on 5-branes. When the gauge groups G_9 and G_5 on 9-branes and 5-branes correspond to the $SU(6)$ and $SU(2)_R$, respectively, the type (ii) strings transform as the bifundamental representation of the $SU(6) \times SU(2)_R$, which is denoted $(\mathbf{6}^*, \mathbf{2})$. On the other hand, the type (i) ((iii)) strings are singlet under the $SU(2)_R$ ($SU(6)$) but are expressed as second rank tensors under the $SU(6)$ ($SU(2)_R$). In the Type I formulation it can be shown that these second rank tensors are antisymmetric. This results from the massless conditions, which can be expressed in terms of the inner products between the root vectors and shift vectors. Thus, the strings starting and ending on 9-branes (5-branes) transform as $(\mathbf{15}, \mathbf{1})$ $((\mathbf{1}, \mathbf{1}))$ under the $SU(6) \times SU(2)_R$. Therefore, the charged matter chiral superfields become $(\mathbf{15}, \mathbf{1})$ and $(\mathbf{6}^*, \mathbf{2})$, which compose a fundamental representation $\mathbf{27}$ of E_6 . Further, the $SU(6)$ gauge anomaly is cancelled within one set of the open strings. The present model has the same charged matter content as the perturbative heterotic string model. This result implies that the phenomenological analyses in Ref.[20] are applicable in the non-perturbative region of the moduli space.

At present it seems that there are a large number of possible paths for connecting the underlying theory with the standard model. In order to explore a realistic scenario, we need to solve many important problems on the basis of the brane picture. New perspectives in string phenomenology will open from further developments in the underlying theory.

Acknowledgements

The authors would like to thank Dr. Y. Imamura for valuable discussions. One of the authors (T. M.) is supported in part by a Grant-in-Aid for Scientific Research, Ministry of Education, Science, Sports and Culture, Japan (Nos. 10140209 and 10640256).

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